ELECTROMECHANICAL CHARACTERIZATION OF PIEZOELECTRIC ACTUATORS SUBJECTED TO A VARIABLE PRELOADING FORCE AT CRYOGENIC TEMPERATURE

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Abstract

Piezoelectric actuators are actually used in Fast Active Cold Tuning Systems (FACTS) for SRF cavities. The characteristics, performances and lifetime of these actuators depend on the preloading force applied by the cavity and the FACTS to the piezostacks. Experimental data are needed for reliable and optimum operation of piezostacks in superconducting protons or electrons linacs. In the frame of the CARE project supported by EU, we designed and constructed a dedicated apparatus for studying the electromechanical behaviour of prototype piezoelectric actuators subjected to variable preloading force at cryogenic temperatures. This device was successfully used for testing piezoelectric actuators prototypes for T in the range 2K-300K. The dielectric properties as well as dynamic properties were measured including the actuator characteristics when used as force sensor. The corresponding data are reported and discussed.

INTRODUCTION

Piezoelectric actuators, which are integrated into the cold tuning system, will be used to compensate [1] the small mechanical deformations of the cavity wall induced by Lorentz forces for accelerating gradients up to 35 MV/m. In order to provide for a reliable operation of the accelerator, the piezoelectric actuators (~30.000-40.000 units for ILC) should function satisfactorily for a period close to machine life duration (~20 years). The corresponding actuator lifetime requirements should be much higher than 3.210^9 cycles (pulsed mode, repetition rate: 5 Hz). Moreover, previous studies showed that the life time of piezostacks depends strongly on the applied preloading pressure P_{Load} (Fig. 1) with an optimum value P_{Load}~100Bars at T=300 K. On the other hand, the actuator displacement versus preloading pressure characteristics (Fig. 2) is not monotonic: the maximum displacement is observed for P_{Load} in the range 20MPa-50MPa. Further, the lifetime versus preload curves depends strongly on actuator material and fabrication process.

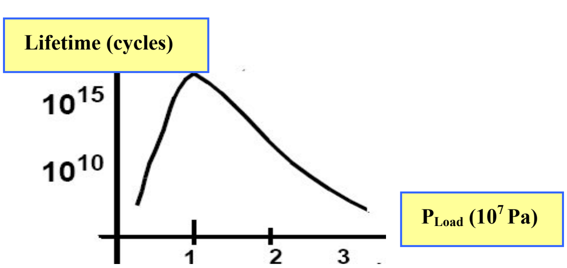

Figure 1: Sketch of lifetime versus preloading pressure.

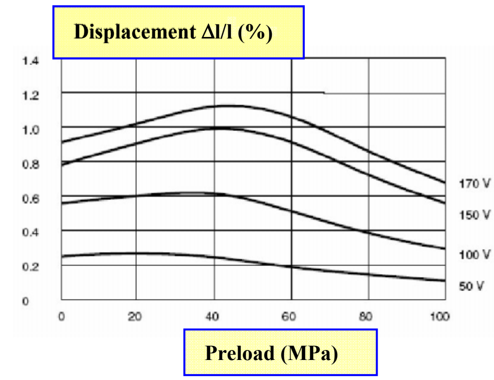

Figure 2: Relative displacement versus preloading pressure at different voltages *(R. Binding et al., see ref. 2)*.

Due to the lack of data for the operating conditions in the actual tuner (i.e., under vacuum and cryogenic conditions), it is necessary to perform an experimental investigation of electromechanical behaviour of actuators subjected to axial preload at cryogenic temperature.

DESCRIPTION OF TEST APPARATUS

The main goals of the experiment are: 1) Study the effect of a variable and controllable axial preload on the electromechanical properties of the piezoelectric actuator (stroke, capacitance, loss factor, impedance, etc), 2) Development of a procedure for applying, adjusting and controlling the preload, 3) Study of the behaviour of piezostacks as force sensor, 4) Measurement of the mechanical stiffness of the actuator. The apparatus should allow to applying and measure a controlled and adjustable axial force in the range 1kN- 4kN to the piezoelectric actuator. Moreover, the piezoelectric actuator should be subjected to this force in an environment similar to the operating conditions in the tuner, namely under vacuum (pressure<10^{-5} mbar) and at cryogenic temperatures. We have designed and constructed a device dedicated to low temperature preloading experiment. The simplest way for applying a vertical downward compressing force is naturally to use gravity. But due to the relatively high value (~100 kg) of the mass (in case of direct load on the actuator axis) needed for achieving force of ~1kN, it is obvious that a lever arm system with a magnification factor ~10-15 (lever arms ratio) should be used. The operating principle of the method is presented in Fig.1. The piezostacks to be tested is enclosed in a stainless steel vacuum chamber which will be immersed in a liquid helium bath. A rotating arm located at room temperature (T~300 K) outside the cryostat allows applying a vertical force (along the actuator axis) to the piezostacks via a high stiffness transmission rod. The preloading force applied to the actuator is simply adjusted by varying the load at the extremity of the rotating arm. At the mechanical equilibrium, the sum of the momentums of all the forces is equal to zero. Assuming a negligible friction on the rotation axis, the preloading F force is simply given by the law of conservation of angular momentum:

$$F = Fc.\left(\frac{L_C}{L_P}\right) + m_A.\left(\frac{L_A}{L_P}\right).g \qquad (1)$$

Where m_A is the masse of the rotating arm, L_P, L_A and L_C are respectively the distances from the rotation axis of the piezostacks axis (L_P), the centre of mass of the arm (L_A) and the loading mass (L_A) and g the gravity constant. Taking into account the available space on the upper flange of the cryostat insert, which support vacuum pumps and other components, the values of the lengths L_P, L_C are respectively 30mm, 430mm leading to a lever arm ratio $r=L_P/L_C$ =14.66. The key element of the preloading system is the rotating arm; consequently it was carefully designed using Finite Element Method numerical simulations in order to verify that it behaves as a rigid body. Note that the simulation model includes the transmission rod and the actuator. The different arms studied and the main results concerning their mechanical behaviour are listed in Table 1.

Table 1: Mechanical characteristics of the rotating arms studied

Cross-section Shape Dimensions *Material*	**ΔXp (μm)**	**ΔXc (mm)**	**ΔXc /ΔXp**	**Bend (mm)**
Rectangle 40x10x500 mm^3 *Aluminium*	66.1	27.5	416	26.5
Rectangular tube (wall thick.: 2mm) 20x20x500 mm^3 *Aluminium*	66.4	12.4	186	11.4
Square 45x45x500 mm^3 ***Stretched steel***	59.4	0.91	**17.7**	0.043

The computed displacements for the square shape cross-section arm made of stretched stainless steel lead to a ratio ΔXc/ΔXp=17.7 of the vertical displacements at the masse location and along the piezostacks axis respectively. This figure is close to the value of lever arm ratio $r=L_P/L_C$ =14.7: the relative difference (i.e., 20%) is due to the finite rigidity of the arm. As expected, due to their low stiffness, the first two aluminium arms of rectangular cross-section shape don't behave as a rigid body. More precisely, they show a high deflexion or bending resulting in a ratio ΔXc/ΔXp one order of magnitude higher than the target r=14.7. Furthermore, the actuator is housed in an evacuated chamber with a removable thin end plate. The apparatus is detailed in a previous report [3]. The operating principle of this device is the following: 1) actuator mode: a voltage is applied to the piezoactuator which expand leading to a deformation of the upper thin sheet; the resulting motion is transmitted to the displacement sensors at 300 via a Φ16 stainless steel rod, 2) Force sensor mode: a loading force is force is applied to the piezostacks via de transmission rod and the response of the actuator (i.e., capacitance and transient voltage) is measured. A close view to the upper part of the preloading system is shown in Fig.3.

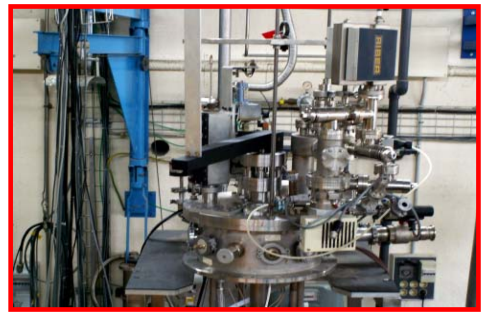

Figure 3: Photograph of the upper part of the insert ready for cryogenic test.

EXPERIMENTAL RESULTS AND DISCUSSION

Repeatability Test at T=4.4K

The sensitivity of a PICMA type piezostacks to a preloading axial force at cryogenic temperature was investigated. The variations of the relative capacitance $\Delta Cp= Cp-Cp_0$, with reference to the capacitance Cp_0 of the actuator when it is subjected to the arm preload F_0=733 N, as function of the preloading force F at T=4.2K are shown in Fig. 4. In order to measure the repeatability of the experimental data, two runs were performed for F increasing from 0 up to 4 kN.

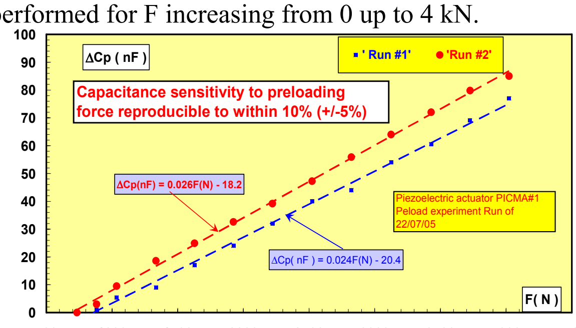

Figure 4: Sensitivity to preloading at T=4.4 K (Reproducibility test), Cp_0=3.134 μF.

The data show a linear behaviour of ΔCp vs. F. Moreover, we observe a good repeatability: the relative variation of the slope ΔCp/ΔF=25nF/kN at T=4.4K for F increasing from 0 to 4 kN between two runs is ±5%.

Sensitivity to Preloading at T=2.05K

The sensitivity of the actuator to preloading was measured at T=2.05 (T=2 K: ILC operating temperature) for increasing and decreasing load (Fig. 5). Non linear effects are observed at low preloading force when F is increased from zero to ~1.3 kN: they are due to friction, stick-slip among non linear phenomena in the preloading device mechanism (rotating arm, bellows). Further, these data clearly show a large hysteresis for increasing and decreasing the preloading force. This hysteretic behaviour could be attributed to the intrinsic irreversibilities in the piezoelectric material itself.

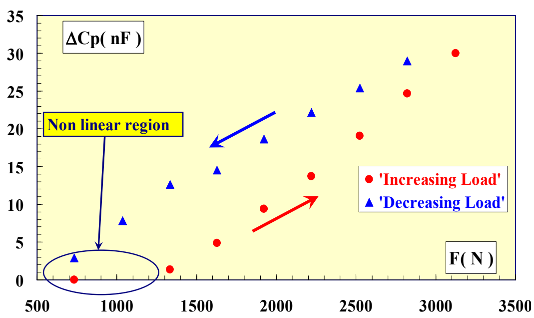

Figure 5: Capacitance versus preload at T=2.05 K, Cp_0=2.879 µF.

At T= 2.05K, the measured sensitivity to preloading are 16nF/kN (respectively 10nF/kN) for F increasing (respectively decreasing).

Effect of Temperature on the Sensitivity to Preloading

We investigate the effect of the actuator temperature on its sensitivity to preloading. Systematic measurements [3] of ΔCp vs. F were performed for T in the range 1.7 K-300K. These results clearly show a linear dependence of the capacitance variation, at a given temperature, with the applied preload in the whole temperature range. Further, the non linear effects observed at T= 2K and low preloading force, were confirmed for all temperatures. Moreover the sensitivity to preloading, in the linear region, depends strongly on the temperature as illustrated in Fig. 6: each data point is simply the slope of the ΔCp vs. F curve at a given T. More precisely, ΔCp/ΔF shows exponential dependence on T: in the increasing preload mode, ΔCp/ΔF increases with T from 16nF/kN at T=2 K to 426nF/kN at T=300 K.

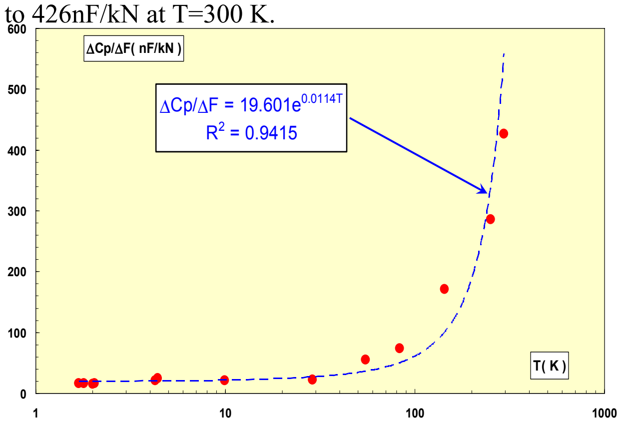

Figure 6: Sensitivity to preloading versus temperature.

Piezostacks as Dynamic Force Sensor

The behaviour of the piezostacks as dynamic force sensor was also studied. The transient response of the actuator to various negative and positive steep preloads variations ΔF=±nx150 N (n=1, 2, 3) was recorded at T=4.2K (Fig.7-Fig.8). The results call for the following remarks: 1) a steep voltage increase (capacitor charging) followed by an exponential decrease (capacitor discharging) is observed, 2) the peak actuator voltage ΔV_p is repeatable (3 %).

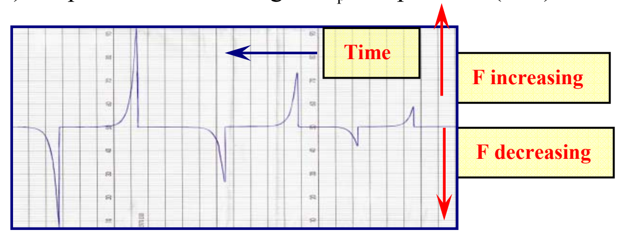

Figure 7: Transient response of a PICMA type actuator to various steep preload variation ΔF=±nx150 N (n=1, 2, 3) at T=4.2 K.

The data of Fig. 7-Fig.8 show the reversibility and the linearity of the response: the peak voltage is proportional to preload variation ($\Delta V_p \propto \Delta F$) and change de sign with ΔF. This behaviour is clearly illustrated in Fig. 8.

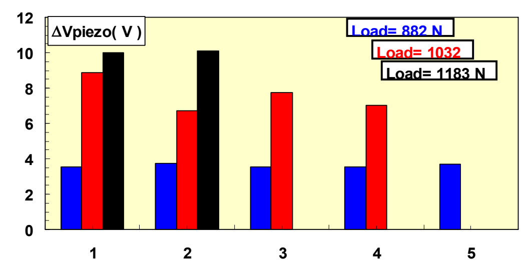

Figure 8: Histogram of the peak voltage recorded during transient response of the actuator to various steep preload variation ΔF=±nx150 N (n=1, 2, 3) at T=4.2 K.

ACKNOWLEDGEMENT

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